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SUMMARY OF EXPERIMENTALLY DETERMINED FACTS CONCERNING THE
BEHAVIOR OF THE BOUNDARY LAYER AND PERFORMANCE OF THE BOUNDARY
LAYER MEASUREMENTS DURING FLIGHT

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16. Abstract The article is a summary report of boundary layer studies carried out by the Engineering Office for Lightweight Construction and Flow Technology, Duisburg, in conjunction with the Institute for Sailing Flight Research, Freiburg im Brsg. Preliminary results of experimental measurements show that: (a) a very thin layer (≈ 0.4 mm) of the boundary layer seems to be accelerated; (b) the static pressure of the outer flow does not remain exactly constant through the boundary layer; (c) an oncoming boundary layer which already turbulent at the suction point can again become laminar behind this point without being completely sucked off.			
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Brief Summary

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The following report gives a survey on projects concerning the subject of boundary layers which have been carried out by Prof. Blume's engineering office in collaboration with the Institute for Sailing Flight Research, Freiburg i Brsg. (IfS) from April 1955 to October 1956.

Based on the results of the preliminary studies done by the IfS (IfS Report 3/1955) the measurement methods were improved and refined and systematic series investigations of the boundary layer were carried out, each time varying the c_a value, the probe position, the amount of suction or the suction pressure. These experiments were performed in such a way so that simultaneously the boundary layer noises were recorded on tape and also the velocity profile within the boundary layer (8 measurement points per 4 mm of layer thickness), amount of suction, suction pressure, air speed and local velocity of the outer flow were recorded by manometer transducers. The interesting parts of the tape recordings were oscillographed. About 120 meters of oscillograph tapes and about 5,000 measurement points are available. Some oscillograms show conspicuous features which still require clarification.

The preliminary results of the measurements are the following:

- a) In the vicinity of the suction point a very thin layer (≈ 0.4 mm) of the boundary layer seems to be accelerated.

* Numbers in the margin indicate pagination in the foreign text.

A smaller portion of this is sucked off, while the larger remaining portion flows away over the suction point and gradually dissipates its energy by friction, whereupon the velocity profile again runs perfectly normal. Here there seems to be certain connections with the transition of the boundary layer into turbulent flow.¹

- b) The static pressure of the outer flow does not hold itself exactly constant through the boundary layer. According to the measurements, it possesses a minimum at the transition of the outer flow to the boundary layer and then increases slightly up to the wing surface.
- c) An oncoming boundary layer which is already turbulent at the suction point can again become laminar behind this point without being completely sucked off.

Findings (a) and (c) are unexpected. The aim of the next study is to prove that these effects actually exist and cannot be attributed to accidental errors of the measuring equipment, since in such a case this could produce new ideas for treating the boundary layer problem.

Introduction

The importance of the laminarization of the boundary layer has become more and more important for the further development of the airplane, the more it has been possible to reduce pressure drag by using advantageous designs to the extent that the drag is about on the same order of magnitude as friction drag. A large number of studies exist on boundary layer problems. Likewise there are some data on wind tunnel experiments. However, flight measurements on

1. This interpretation of the effect could not be upheld on the basis of later measurements.

actually constructed wings are very scanty, although it is precisely these measurements which are of greatest importance because of the Reynolds number, degree of turbulence of the atmosphere and natural surface quality both with respect to waviness and roughness.

Practical boundary layer measurements were first begun in Germany after the Second World War in 1952 by the "Institute for Sailing Flight Research, Freiburg im Brsg." (IfS). The experiments were then continued in 1954 with funds provided by the Federal Traffic Ministry. These studies are described in the IfS report 3/1955, a brief summary of which was published in the journal Luftfahrttechnik [Aviation Technology] Vol. 1, No. 6 (1955).

When these studies were concluded in the spring of 1959 the following facilities and results were available for future use:

- a) test airplane with built-in suction unit;
- b) practical experience with test surfaces on the airplane wing;
- c) practical data on the familiar methods for determining the nature of the boundary layers;
- d) methods developed for objectively determining the position of the transition point using a microphone probe, tape recorder and oscillograph;
- e) preliminary experiments to determine the drag using the momentum loss method;
- f) results with suction slots.

As a result of another research contract being awarded by the Federal Traffic Ministry it was possible to obtain further data in collaboration with the IfS which brought us another step closer to our final objective of making a completely laminar airplane wing.

At the start of the work a decision had to be made as to which way would be the best one to take. There were two possibilities open to us. Either by varying the design of the test surface and the arrangement of suction points we could test how far we could bring back the transition point, or by taking measurements we could try to get a closer idea of the actual processes in the boundary layer thus to recognize causes and effects in accordance with the saying of Lord Kelvin: "Knowledge means measurement." After preliminary experiments had shown that it was unsuitable to place suction slots -- since in the first place very high demands have to be placed on the form of the slot and, secondly, in spite of its very small width, the slot represents a relatively large interference into the flow -- it was decided to take the second path which alone could provide the basis for a systematic procedure. The result of the study has shown that this decision was correct. The view we have today of the suction problem is different from the one we had a year ago. Nevertheless, it still has to be proved that the measured effects actually exist and are not to be attributed to accidental errors in the measurement apparatus. These checks will be performed at the very beginning in a continuation of these studies, since they are of fundamental importance for further considerations. /6

Here we would like to thank the Federal Traffic Ministry for supporting these studies. Much thanks is also due to the Director and members of the Institute for Sailing Flight Research, Freiburg, above all Dr. Froweing, Mr. Wieser and Miss Häfner who through their personal effort contributed considerably to the success of these studies. Furthermore, we are greatly indebted to Director Morat and to the Hellige Co., Freiburg for their frequent assistance which they gave us in a number of ways.

The following report is divided up into the individual substudies and the equipment and literature references are summarized according to chapter.

A. Brief Literature Review of the Most Important Experimental Studies Which Deal with Boundary Layer Suction in Order to Reduce c_w

The idea of keeping the boundary layer laminar for a longer period of time along a body in a flow by using appropriate suction and thus reduce the friction drag of the body was probably expressed for the first time by B. M. Jones in 1928 and later by B. S. Shentstone in 1937. This idea states: only so little suction should be applied so as to produce considerable stabilization of the laminar boundary layer, in the process of which, however, the pressure distribution along the body, i.e. the entire flow pattern, is not changed. The stabilizing effect is essentially achieved by the fact that at all times only the portions of the boundary layer with the least amount of energy, i.e. next to the wall, are removed and thus the velocity profiles maintain a more stable, fuller form. By contrast, up to that time -- following Prandtl's line of thinking -- in all suction experiments the entire boundary layer was always removed from the flow with the aim of pushing out the boundary layer separation and thus maintaining the flow shapes which particularly resemble the potential flows and to some extent also possess their good properties. Given this process the amount of suction is allowed to increase further, then the effect on the potential flow becomes increasingly stronger and quite unusual flow patterns are obtained, sometimes with surprising properties.

In the years prior to the last war various authors theoretically showed the possibility of stabilizing the laminar boundary layer by using suction and in this connection

continuous suction was always assumed for purposes of calculation. From a technical standpoint, such continuous suction can be achieved, for example, by porous walls. From a practical standpoint, however, it is somewhat similar and accordingly much more popular to achieve the suction by means of one or several individual slots. On this point the general comments must be made that, with respect to the desired stabilizing effect, individual slots are extremely poor, for stabilization of the boundary layer -- as already mentioned -- is equivalent to a uniform as possible change in the boundary layer profiles to a more complete form.

Such a change in velocity can be obtained only with slots of the best design, but even then only rather quickly. Even with a slight change in the shape of the slot or other experimental conditions, the substantial interference into the boundary layer flow most often leads to turbulence.

The first experimental tests on c_w reduction by means of suction were conducted almost at the same time (around 1940) by H. Holstein in Göttingen and by the group under Prof. Ackeret in Zurich. For the most part the results of these studies are recorded in [1], [2], [3] and [4]. A large portion of the Zurich experiments were later summarized by W. Pfenninger in [5].

These first experiments exclusively involved wind tunnel measurements on (carefully constructed) models in which suction slots were used. To begin with, Holstein found that in fact, whenever the first slot is in front of the transition point without suction, this transition point shifts further towards the rear. By arranging additional slots he was then able, under certain other experimental conditions, to achieve good reduction in drag by maintaining the laminar flow even if

the suction power is taken into account in this connection. The Zurich experiments turned out in a similar manner. After studies on the flow in the vicinity of individual slots, it was possible with the aid of 14-35 suction slots to keep the boundary layer laminar for a fairly long period. The parameters measured in these experiments, besides c_w , were primarily the suction coefficients c_Q and c_p and velocity profiles in the boundary layer whose shape indeed represent a measure of the degree of stabilization. All of these experiments fundamentally showed that the success of maintaining laminar flow by suction is extremely dependent on careful slot construction and on a highly smooth surface, since otherwise the flow is easily so strongly disturbed that the transition into turbulent flow occurs immediately. This great sensitivity of the results make direct application in practice fairly difficult.

The experiments performed in the United States and England during the war in this area did not at all become known to us or only very much later. For a long time a group of scientists at Langley Aeronautical Laboratory in the United States has been working on c_w reduction by suction. Their test results -- provided they are not secret -- were published in the NACA Reports [6]-[12].

The experiments discussed in [6], [7] and [8] use slots for suction. In the experiments discussed in [9]-[12] it was attempted to produce continuous suction by means of suitable porous substances. All of the tests were carried out in a wind tunnel. Only the measurements described in [6] -- with respect to a lower degree of turbulence -- were carried out on a small airfoil model attached to an airplane. However, at Reynolds numbers up to 26.5×10^6 they resulted in only a small shift of the transition point by about 12% of the chord length. Otherwise the results obtained using slots again completely corresponded with the findings obtained in Göttingen and Zurich:

in order to keep the boundary layer laminar for a sufficiently long time very many slots are required. In [8], for example, 41 are used on each profile side with result that the flow remained laminar up to 91% of the chord length at Reynolds numbers up to 10×10^6 . These results were achieved, however, only with great expense to obtain the best construction of the slot form and the best surface quality. Therefore again the results can be applied only with great difficulty in practice. Because of this finding, shortly after the war suction experiments with porous surfaces were begun at Langley Field. To begin with, wing models made of a wooden lattice were used which was covered with filter paper [9]. The profile surface was extremely deformed by the aerodynamic forces, and the surface quality was also fairly poor. In spite of these considerable irregularities, nevertheless at small Reynolds number (about 2×10^6) a certain stabilization of the boundary layer occurred, quite in contrast to the suction process using slots.

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The wind tunnel experiments which were afterwards performed with models made of porous bronze then also showed that up to Reynolds numbers of 20×10^6 the boundary layer could be kept completely laminar as long as the surface is not too rough and blowout does not by chance occur at one point due to various pressure conditions along the profile contour. Another difficulty which turned up in these experiments was that the porous walls clogged extremely easily.

Raspet [13], [14] and [15] and somewhat later Carmichael [16], using sail planes, tried to translate into practice the quite good results obtained with continuous suction.

A. Raspet produced the porous wall necessary for continuous suction by performing many small holes close together into the covering of the wing.

Then in order to keep the boundary layer laminar at a Reynolds number of 3×10^6 up to 95% of the chord length requires a suction coefficient $c_Q = 5 \times 10^{-4}$, which is approximately 4 times the theoretical value calculated by A. Ulrich for stabilization of the boundary layer on a flat plate. However, this result depends very strongly on the suction pressure c_p , i.e. it is valid only in a very narrowly limited angle of attack range.

Besides the experimental studies on c_w reduction by suction in the United States mentioned here, certainly there is also a very large number of results in the United States which have been kept secret up to now. Moreover, most recently a number of articles on this topic have come out. Unfortunately, however, the only ones of these known to this reporter are articles [17], [18] and [19].

From Great Britian, besides a number of theoretical papers on boundary layer suction for c_w reduction, a small number of experimental results have been published only very lately. Again this is certainly due to the strict secrecy regulations. It seems, however, that in some respects investigators in Great Britian have already gone very far into this problem.

In articles [20] and [21], besides quite interesting general considerations on the problem, above all experiments are described with a bronze airfoil model suspended underneath an airplane. Suction is achieved by means of several slots on the model and also by porous bronze. Here again the unfavorable effect of defective surface quality is observed. Thus, among other things, it was found by Jones and Head that, for example, small paper discs measuring 1.5 mm in diameter and 0.125 mm thick stuck onto the model have an unstabilizing effect if the displacement thickness is around 0.45 mm.

A quite comprehensive series of suction experiments for c_w reduction has been performed at Handley Page by G. Lachmann. Up to the beginning of 1956 these were discussed only in broad terms by Lachmann in a few general articles such as [22], [23] and [24]. Among other things, he stated that the possibility of keeping the boundary layer laminar in flight up to the trailing edge of the wing can be regarded as proven even up to mach numbers in the vicinity of the critical mach number.

In so doing, however, the surface quality must be especially good and waviness as well as an irregular suction structure must be avoided.

In the Brancker Memorial Lecture -- printed in [25] -- Sir A. Hall mentioned some quite interesting results from British suction experiments on a "Vampire" which were performed by G. Lachmann. Some information on this is given in two general articles dated April 1956 (no authors given). Light metal test surfaces were slipped over the wing of the Vampire. In the best version they had 39 rows of small suction holes with a diameter of about 0.25 mm. With relatively small suction amounts (according to Sir A. Hall [25] the average suction velocity is supposed to be 0.08 meters per second) a reduction in drag of up to 82.5% was achieved -- with pump output taken into account. To check the effectiveness of the suction among other things measurements of the boundary layer velocity profiles were performed with a small rack of pressure probes.

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